



AEROSPACE RECOMMENDED PRACTICE

ARP7094™

Issued

2025-02

Recommended Practice for Using Modeling and Simulation
for Certification of Aircraft, Products, and Systems

RATIONALE

This SAE Aerospace Recommended Practice (ARP) establishes a process for using modeling and simulation (M&S) as a method of compliance for meeting regulatory requirements that have been traditionally demonstrated through analysis, ground testing, and flight testing. While M&S has seen limited use for certification in the past, the recent introduction of innovative new aircraft and systems, which use highly complex technologies that are difficult, or even impossible, to test fully, necessitates a much more rigorous process for their use.

1. INTRODUCTION

1.1 Scope

The scope of this ARP is as follows:

- Use of M&S for type certification of the Advanced Air Mobility (AAM) aircraft, product, or system. However, this does not preclude this ARP being used for certification of other aircraft types and associated products and systems.
- This ARP is not applicable to flight simulation training device (FSTD) qualifications or pilot certification. If a qualified FSTD is proposed for aircraft, product, or system certification, it must demonstrate sufficient M&S substantiation to meet the related requirement.
- Structural design and modeling are not addressed by this document.
- EMI/EMC certification is not addressed by this document.

1.2 Background

The SAE International G-35 Modeling, Simulation, and Training for Emerging Aviation Technologies and Concepts Committee brings together experts in manufacturing, design, and operations with regulators and academia to develop consensus-based standards to address the needs of the burgeoning AAM industry. These emerging aircraft designs require significant changes to the certification process for the aircraft and its associated systems and for supporting training methods, personnel, and environment. The use of M&S for certification credit is one part of the certification process that requires this sort of change.

Historically, the certification process has seen use of M&S at only the highest system levels, primarily to re-create failures seen in real life. This use of M&S can increase the safety of aviation systems by providing a safe mechanism to test corner cases that would otherwise be too dangerous to fly. When this technique has been proposed for this purpose, acceptance of the model or simulation by the certification authority has been somewhat arbitrary without a standard for evaluation for acceptance. Expansion of M&S to further testing, including nominal cases, has therefore been slow.

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However, M&S has supported type certification in aviation for decades, although they have rarely been used as primary methods of compliance despite their proven reliability. Current advances in complex systems, particularly tightly coupled flight controls and power plants, are increasingly common in general aviation, and the numerous interactions among such systems make physical test of all potential cases impractical. The use of validated models and simulations allows a much wider range of tests and enables early assessment of flight performance and characteristics as well as the performance of the aircraft, power plants, propulsors, and systems. M&S is now recognized as a standard method for certification. This recommended practice was written to establish a process by which M&S can be incorporated into the path to certification, avoiding the arbitrary nature of the historical process and encouraging more widespread use. While this recommended practice is intended to address new and emerging aircraft designs, it is also applicable to conventional aircraft that incorporate new technologies and capabilities.

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2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP4754B Guidelines for Development of Civil Aircraft and Systems

2.1.2 Code of Federal Regulations (CFR) Publications

Available from United States Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

14 CFR Part 60 Flight Simulation Training Device Initial and Continuing Qualification and Use

2.1.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

CS-FSTD(A) Aeroplane Flight Simulation Training Devices

CS-FSTD(H) Helicopter Flight Simulation Training Devices

2.1.4 ICAO Publications

Available from International Civil Aviation Organization, 999 University Street, Montreal, Quebec H3C 5H7, Canada, Tel: +1 514-954-8219, <http://www.icao.int/>.

ICAO 9625 Manual of Criteria for the Qualification of Flight Simulation Training Devices (Volume 1 - Aeroplanes, Fourth Edition, 2015)

2.1.5 RAeS Publications

Available from the Royal Aeronautical Society, Tel: +44 (0) 20 7670 4352, <https://www.aerosociety.com/>.

Aeroplane Flight Simulation Training Device Evaluation Handbook, Volume 1

2.1.6 Transport Canada Publications

Available from Transport Canada, Tower C, Place de Ville, 330 Sparks Street Ottawa, Ontario K1A 0N5, Tel: 1-800-305-2059, www.tc.gc.ca.

TP 9685E Aeroplane and Rotorcraft Simulator Manual

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARINC 610C Guidance for Design of Aircraft Equipment and Software for Use in Training Devices

2.2.2 Code of Federal Regulations (CFR) Publications

Available from United States Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

- 14 CFR Part 21 Certification Procedures for Products and Articles
- 14 CFR Part 23 Airworthiness Standards: Normal Category Airplanes
- 14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes (FAA)
- 14 CFR Part 27 Airworthiness Standards: Normal Category Rotorcraft (FAA)
- 14 CFR Part 29 Airworthiness Standards: Transport Category Rotorcraft (FAA)
- 14 CFR Part 33 Airworthiness Standards: Aircraft Engines
- 14 CFR Part 35 Airworthiness Standards: Propellers

2.2.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

EC Reg 748/2012 Annex I - Part 21

- CS-23 Normal, Utility, Aerobatic and Commuter Airplanes
- CS-25 Large Airplanes
- CS-27 Small Rotorcraft
- CS-29 Large Rotorcraft
- CS-E Engines
- CS-P Propellers
- SC-VTOL Special Condition for VTOL and Means of Compliance

2.2.4 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

8110.4C FAA Order, Type Certification, with Change 7

AC 21.17-4 Type Certification - Powered-lift

AC 23.2010-1 FAA Accepted Means of Compliance Process for 14 CFR Part 23

2.2.5 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

An Integrated Modeling, Simulation and Analysis Framework for Engineering Complex Systems

2.2.6 NATO Publications

Copies of these documents are available online at <https://www.sto.nato.int/publications/>.

STO-TR-AVT-296-UU Rotorcraft Flight Simulation Model Fidelity Improvement and Assessment by the North Atlantic Treaty Organization Science and Technology Organization (NATO S&TO)

2.2.7 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-178C/ED-12C Software Considerations in Airborne Systems and Equipment Certification

DO-330/ED-215 Software tool qualification considerations.

DO-331/ED-218 Model-Based Development and Verification Supplement to DO-178C and DO-278A

2.2.8 Transport Canada Publications

Available from Transport Canada, Tower C, Place de Ville, 330 Sparks Street Ottawa, Ontario K1A 0N5, Tel: 1-800-305-2059, www.tc.gc.ca.

AWM 523N Normal Category Aeroplanes

AWM 525 Transport Category Aeroplanes

AWM 527 Normal Category Rotorcraft

AWM 529 Transport Category Rotorcraft

AWM-533 Aircraft Engines

AWM-535 Propellers

2.3 Abbreviations

The following abbreviations are provided for information purposes only.

AAM	advanced air mobility
AC	Advisory Circular (FAA)
AFHA	aircraft functional hazard assessment
AI	artificial intelligence
ANAC	Agência Nacional de Aviação Civil (Brazil)
AR	augmented reality
ARP	Aerospace Recommended Practice (SAE)
ARAC	Aviation Rulemaking Advisory Committee
AS	Aerospace Standard (SAE)
ASTM	ASTM International
AWM	Airworthiness Manual (TCAN)
CAA	Civil Aviation Authority (United Kingdom)
CFR	Code of Federal Regulations (FAA)
CS	Certification Specification (EASA)
EASA	European Union Aviation Safety Agency
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EUROCAE	European Organisation for Civil Aviation Equipment
eVTOL	electric vertical takeoff and landing
FAA	Federal Aviation Administration
FSTD	flight simulation training device
HF	human factors
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
M&S	modeling and simulation
MBD	model-based definition
MR	mixed reality

NATO	North Atlantic Treaty Organization
PSCP	project specific certification plan
RAeS	Royal Aeronautical Society
RTCA	Radio Technical Commission for Aeronautics
S&TO	Science & Technology Organization (NATO)
SAE	SAE International
SC	supplemental certification (EASA)
SCR	simulation for credit review
SME	subject matter expert
STOL	short takeoff and landing
TC	type certification
TCAN	Transport Canada
UAM	urban air mobility
VR	virtual reality
VTOL	vertical takeoff and landing
XR	extended reality

2.4 Definitions

ADVANCED AIR MOBILITY (AAM): Operations with novel aircraft designs that do not fall into a traditional category, and that have vertical takeoff and landing capabilities and distributed propulsion features, may be operated in unmanned/uncrewed configurations that are conceived to offer a new air mobility of people and cargo in congested (urban) areas based on an integrated air and ground-based infrastructure. AAM describes a diverse array of aircraft types (such as manned and unmanned) whose designs are enabled by ongoing innovations, particularly in the areas of hybrid and electrification of propulsion systems, energy storage, lightweight materials, digitalization, and automation. These innovations have made possible an array of novel designs spanning multi-rotor, tilt wing, tilt-rotor, and powered wing and offer short takeoff and landing (STOL) through to vertical takeoff and landing (VTOL) capabilities.

CERTIFICATION AUTHORITY: Organization or person responsible for granting approval in accordance with applicable regulations.

CONFIGURATION CONTROL: The method of controlling, approving, and tracking changes to a product's deliverables and processes.

CONFORMITY: Aircraft that conforms to its type design and is configured/bridged to the approved program and operations.

ELECTRIC VERTICAL TAKEOFF AND LANDING (eVTOL): eVTOL aircraft may be powered by hybrid electric systems, batteries, or potentially hydrogen fuel cells. An eVTOL aircraft uses electric power to hover, take off, and land vertically. This technology came about thanks to major advances in electric propulsion and the growing need for new vehicles for urban air mobility.

EMULATION: Mimics the output behavior to match an existing target. The internal state of the emulation mechanism does not have to accurately reflect the internal state of the target that it is emulating.

FLIGHT TESTING: Testing where the intent is to establish the aircraft flight characteristics by a qualified test pilot and that is used as a truth source to validate the M&S.

HARDWARE-IN-THE-LOOP: A testing methodology used to simulate the behavior of complex systems. It involves integrating actual hardware components with simulation models to test and validate the performance and functionality of control systems in a controlled environment.

HUMAN-IN-THE-LOOP: Human is in direct control of the systems.

HUMAN-ON-THE-LOOP: Human has supervisory control of the systems. Human actively monitors the systems and can take full control when required or desired.

HUMAN-OUT-OF-THE-LOOP: Human delegates all authority to the system once the execution of the function is enabled. Automated processes are in control of the system and have the authority to perform actions without the human having awareness of the actions being taken.

HUMAN-OVER-THE-LOOP: Human has supervisory control of the systems. Human passively monitors the systems and is informed by automation if, and what, action is required. Human is engaged by the automation either for exceptions that are not reconcilable or as part of rule set escalation.

MEANS OF COMPLIANCE: A detailed design standard that, if met, accomplishes the safety intent of the regulation, is used by an applicant to show compliance with the applicable airworthiness criteria, and is accepted by the Certification Authority. A means of compliance is one method, but not the only method, to show compliance with a regulatory requirement. For this document, a specific description of HOW the models and simulations are used would constitute one way to establish a means of compliance for them.

METHOD OF COMPLIANCE: A description of how compliance will be shown (e.g., ground test, flight test, analysis, similarity, etc.). For the purposes of this document, the use of models and simulations (or a formal name appropriately established) would be a method of compliance. The description of the method of compliance should be sufficient to determine that all necessary compliance-related data will be collected and all findings can be made.

MODEL: A mathematical, physical, or conceptual representation of a given set of aspects of a system/function/item that is used for its analysis, implementation, simulation, or code generation and that has unambiguous, well-defined syntax and semantics.

MODELING: The process of creating a model.

SCALABLE SIMULATION: The ability for a simulation to be adapted for use in environments of variable complexity.

SIMULATED: A functional representation of something, such as a physical system.

SIMULATION: A simulation is the imitation of the operation of a real-world process or system over time. Simulations require the use of models; the model represents the key characteristics or behaviors of the selected system or process, whereas the simulation represents the evolution of the model over time. Computers are often used to execute the simulation.

TYPE CERTIFICATION: The approval of the design of the aircraft and all component parts. It signifies the design is in compliance with the applicable standards.

VALIDATION: The process of determining the degree to which a model or a simulation is an accurate representation of the real world from the perspective of the intended uses of the M&S.

VERIFICATION: The process of determining that an M&S implementation accurately represents the intended description and function.

3. CERTIFICATION PROCESS USING SIMULATION

3.1 Overview

Figure 1 shows an optional certification process that may be used to include the use of M&S. Further details are provided in Sections 4 through 7.

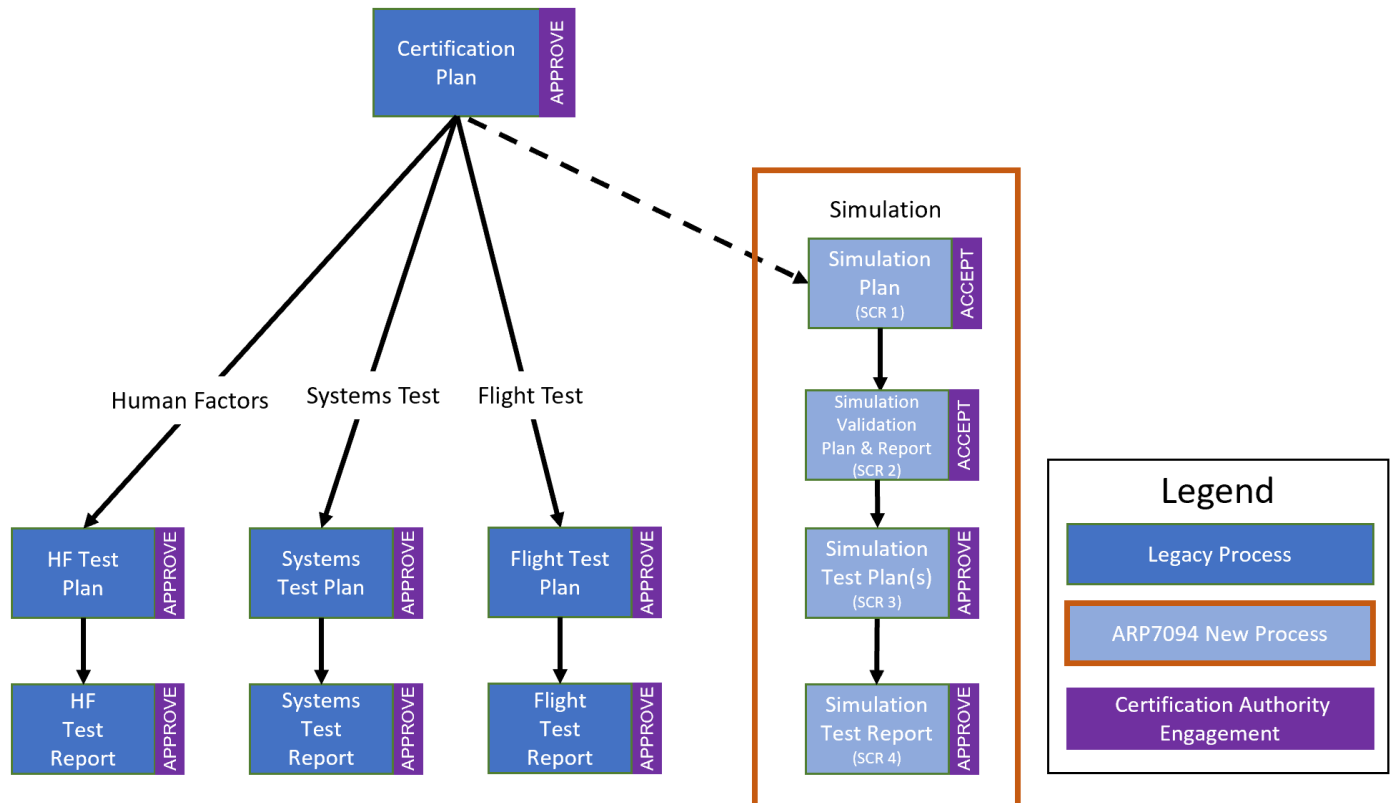


Figure 1 - Optional M&S certification path

3.2 Simulation for Credit Review (SCR) Process

A review process ensures close coordination between the applicant and Certification Authority during the development and eventual certification. The certification process using simulation should utilize the Simulation for Credit Review (SCR) process to ensure the same close coordination between the applicant and the Certification Authority. The SCR should include the following reviews to provide confidence in the simulation for the end product (simulation for a system, systems, or integrated systems up to and including the aircraft system as a whole) to be used in lieu of extensive certification flight or system testing.

SCR1: A review should be conducted when the Simulation Plan is ready to be submitted to the Certification Authority (see Section 4). The Simulation Plan can be a stand-alone document or included in the Certification Plan, or equivalent.

SCR2: A review should be conducted when the Simulation Validation Plan and Simulation Validation Report are ready to be submitted to the Certification Authority (see Section 5).

SCR3: A review should be conducted when the Simulation Test Plan is ready to be submitted to the Certification Authority or delegated representative (see Section 6).

SCR4: A final review should be conducted when the Simulation Test Report is ready to be submitted to the Certification Authority or delegated representative (see Section 7).

4. SIMULATION PLAN

4.1 Overview

The Simulation Plan describes the intent and scope of the simulation.

This document describes how M&S should be used for certification. It is advised that if this ARP is to be used, the Simulation Plan is described for the applicant's project as a method of compliance.

The Simulation Plan should fulfill the Simulation Plan objectives described throughout this section.

The Simulation Plan should contain the following:

- Descriptions of the systems, components, features, etc., that compliance is being shown for
- Applicable regulations
- Proposed simulations
- Scalable simulations
- Simulation environment
- Configuration management plan for simulations: repositories, change management
- Reference/design data used to create and verify the simulation
- Limitations of the simulation
- Testing methods
- Test witnessing according to the Certification Authority test witnessing guidelines

It should be noted that if any of the objectives change, the Simulation Plan will have to be updated.

4.1.1 Simulation Plan Objective 1: Descriptions

Describe the aircraft systems and features for which the simulation will be used to show compliance.

4.1.1.1 System Testing

The Simulation Plan should include a description of all testing where the intent is to certify one or more of the systems that will be a part of the final aircraft. Not all systems on the aircraft need to be included in this description; rather, description should be included only for the testing of systems where simulation will be used for certification. Following are some examples of systems that the engineering team may validate via appropriate simulation:

- Electrical
- Hydraulic
- Mechanical
- Avionics
- Environmental control systems
- Propulsion components or system
- Flight control system
- Energy/fuel storage and distribution
- Ground control station
- Command and control link

4.1.1.2 Human Factors Testing

The simulation plan should include a description of all testing that involves validation of human machine interfaces from the aircraft. Similar to system testing, the Simulation Plan only needs to describe the planned testing of those human factors features for which simulation is planned to be used for certification.

4.1.1.3 Flight Testing

The Simulation Plan should describe any testing that would normally be conducted as part of an aircraft flight test plan but is instead seeking certification based on testing within the simulation.

4.1.2 Simulation Plan Objective 2: Applicable Regulations

Document the specific regulations and other applicable material that the simulation will be used to show compliance for.

The Simulation Plan should include any applicable:

- Specific regulations
- Existing guidance
- Advisory material
- Airworthiness criteria

For each such item included in the Simulation Plan, a description should be provided of how the simulation will support showing compliance. This includes documentation of how the simulation will affect the system safety assessment.

4.1.3 Simulation Plan Objective 3: Simulation Environment

Describe the architecture and components of the planned simulation or simulations.

The Simulation Plan, for each simulation, should describe the following, as applicable:

- Specific model, models, or simulation being proposed: Give an overview of the simulation and what is being modeled. This should include modeling for the overall aircraft and its aerodynamics as well as the lower-level models from which the overall simulation is composed.
- Aircraft hardware/software: Describe components of the aircraft that are being modeled within the simulation. This should include both hardware and software components.
- Hardware/Software emulation: If an emulation setup is being used to provide the functionality of a hardware or software component or subsystem, then a description of the emulation should be provided.
- Piloted versus non-piloted: Describe whether the simulation is intended to be operated by a pilot or whether it is non-piloted. In both cases, the interfaces to control the simulation should be described.
- Flight deck representativeness (visual, audio, motion, physical, etc.): For simulations that include representation of the flight deck, these features and components should be described in the Simulation Plan.

In addition to the architectural and model description, the Simulation Plan should define the computational environment or framework to be used for simulation testing. This can include, but is not limited to, the following:

- Computing devices
- Immersive technologies (VR, AR, MR, XR)
- Fixed-based devices
- Motion-based devices and capabilities

4.1.4 Simulation Plan Objective 4: Scalable Simulations

If applicable, elaborate on the use of scalable simulations.

- Scalable simulations, when utilized, should have their fidelity defined in the Simulation Plan, along with documentation as to how the fidelity of this simulation is appropriate for the planned uses.

4.1.5 Simulation Plan Objective 5: Configuration Management

Plan the configuration management and update processes for the simulation.

To be used for certification, the simulation needs to conform to the systems being certified. Within the simulation plan, the following should be described in detail:

- Process for ensuring that the simulation remains up to date with the aircraft design and test data.
- Impact of physical and control design changes to the model and operational scenarios.
- Description of the model update process.
- Description of the impact of model changes or updates to anticipated types of test cases (as described in Simulation Plan Objective 1; see 4.1.1).
- Configuration identification.
- Baselines and traceability.
- Problem reporting, tracking, and disposition.
- Change control.
- Change review.
- Archive and retrieval.
- Software load control.
- Simulation environment control.
- Simulation data control.

Applicants can refer to their existing configuration management process (refer to 5.6 of ARP4754B) and ensure that M&S are included.

4.1.6 Simulation Plan Objective 6: Design and Reference Data

Describe the reference data and design information that is used to create the simulation.

The Simulation Plan should include information on the applicable data that will be used to create the simulation, including:

- System design documentation, including (if applicable):
 - Aircraft wiring diagrams, schematics
 - Aerodynamic, structural, mass and inertia, geometric properties
 - System interface data
- Standards, procedures, and operations manuals

- Simulation approach and methods:
 - Physics-based models
 - Empirical models
- Lab test data
- Performance reference data
- Environmental effects
- Operational scenarios
- Vendor data or simulations
- Legacy program simulations

Within the Simulation Plan, this information may be co-located with the simulation architecture and environment description used to fulfill Simulation Plan Objective 3 (see 4.1.3).

4.1.7 Simulation Plan Objective 7: Limitations of the Simulation

Define the anticipated limitations of the simulation.

The Simulation Plan should include any applicable limitation(s) while using the simulation, including:

- System fidelity and accuracy
- Physical configuration
- Performance envelope
- Component maturity
- Non-normal conditions
- Motion effects
- Real-time operation

These limitations should be discussed in the context of Simulation Plan Objectives 1 and 2, such that it is clear from the Simulation Plan that the intended testing to be conducted in simulation is not obstructed by the limitations of the simulation or component models.

4.1.8 Simulation Plan Objective 8: Testing Methods

Define testing methods that the simulation will be used for.

A variety of testing methods can be used with the simulation, including:

- Hardware-in-the-loop
- Human-in-the-loop
- Human-on-the-loop
- Human-over-the-loop
- Bench/rig testing
- Desktop simulation

The Simulation Plan should define which of these methods of testing will be used to support the Simulation Test Plan (see Section 6). Within the description of each test method, the key requirements that the simulation needs to fulfill to enable that test method should be outlined.

4.1.9 Simulation Plan Objective 9: Test Witnessing Plan

Document test witnessing requirements.

- The Simulation Plan should propose which tests will require witnessing and by what representative or designated representative.
- For tests that do not require witnessing, the Simulation Plan should propose how the executed tests and results will be submitted to support the Simulation Test Plan.

4.1.10 Simulation Plan Objective 10: Test Scopes and Regulation Mapping

Create mapping between the regulations for which compliance is sought and the simulations that will be used to prove compliance with those regulations.

The Simulation Plan should document the applicant's intent to show compliance with specific regulations by using a validated simulation. Broadly, the test scopes that could be partially conducted in simulation are in the areas of System Testing, Human Factors, and Flight Testing. The Simulation Plan should thus describe, for each regulation, how simulation will be used for certification and why the simulation will be valid for such testing.

4.2 System Testing

4.2.1 Scope

This section covers the specific minimum considerations that should be addressed by the applicant when preparing the Simulation Plan for System Testing.

4.2.2 Applicable Regulations for System Testing

- Certification by simulation can be sought for all applicable regulations, equivalent guidance, advisory material, or airworthiness criteria.
- See 2.1 for applicable regulations.

4.2.3 Proposed Simulations for System Testing

- Required simulations and emulations should be generic, representative, or specific depending on the level of fidelity required (see Appendix B) for the test cases.
 - The target component/system hardware can be emulated.
 - The target component/system software can be simulated if based on data generated by the conformed configuration software or functionally equivalent.
 - The interfacing system's hardware and software can be simulated.
- The target component/system should be integrated with its interfacing systems.
- Flight deck should be representative when pilot evaluation is required.

4.2.4 Scalable Simulations for System Testing

- Simulations/models of the appropriate fidelity can be used for component/system testing as needed for the specific function being tested.

4.2.5 Design and Reference Data for System Testing

- Data should be appropriate to the scope of the testing being performed.

4.2.6 Limitations of the Simulation for System Testing

- Limitations should be provided for parameters that affect the operation and/or behavior of the target component/system, including hardware and software.

4.2.7 Testing Methods for System Testing

- Automated, hardware-in-the-loop, and bench testing used for component testing
- Automated, human-in-the-loop, and bench testing used for system testing

4.2.8 Witnessing for System Testing

- The Simulation Plan should propose what tests will require witnessing and determine the Certification Authority or delegated representative.
- For tests that do not require witnessing, the Simulation Plan should propose how the executed tests and results will be submitted to support the Simulation Test Plan.

4.3 Human Factors Testing

4.3.1 Scope

This section covers the specific minimum considerations that should be addressed by the applicant when preparing the Simulation Plan for Human Factors Testing.

4.3.2 Applicable Regulations for Human Factors Testing

- Certification by simulation sought for all applicable regulations, equivalent guidance, advisory material, or airworthiness criteria.
- See 2.1 for applicable regulations.

4.3.3 Proposed Simulations for Human Factors Testing

- Critical aircraft performance, flight characteristics, and systems simulations, including but not limited to flight dynamics, flight controls, ground reactions, and propulsion; should be specific (see Appendix B).
- Other required simulations and emulations should be generic, representative, or specific depending on the level of fidelity required (see Appendix B) for the test cases.
- Conformity options include:
 - Simulated aircraft hardware
 - Emulated aircraft software, if based on data generated by the conformed configuration software or functionally equivalent
 - Emulated interfacing systems hardware and software
 - Conformed hardware
- Flight deck should conform to the final type design for all pilot tasks, whether automated or performed by a human.

4.3.4 Scalable Simulations for Human Factors Testing

- Scalable models used for component/system testing if appropriate for the specific function being tested. Scalable models of humans can be used if based on requirements of the end user of the system.

4.3.5 Design and Reference Data for Human Factors Testing

- Data should be appropriate to the scope of the testing being performed.

4.3.6 Limitations of the Simulation for Human Factors Testing

- Limitations should be provided for parameters that affect the operation and/or behavior of the target component/system.
- Limitations should be provided for parameters that affect the flight dynamics for all pilot tasks, whether automated or performed by a human.

4.3.7 Testing Methods for Human Factors Testing

- Automated and bench testing used for component testing.
- Automated, human-in-the-loop, and bench testing used for system testing.

4.3.8 Witnessing for Human Factors Testing

- The Simulation Plan should propose what tests will require witnessing and determine the Certification Authority or delegated representative.
- For tests that do not require witnessing, the Simulation Plan proposes how the executed tests and results will be submitted to support the Simulation Test Plan.

4.4 Flight Testing

4.4.1 Scope

This section covers the specific minimum considerations that should be addressed by the applicant when preparing the Simulation Plan for Flight Testing.

4.4.2 Applicable Regulations for Flight Testing

- Certification by simulation sought for all applicable regulations, equivalent guidance, advisory material, or airworthiness criteria.
- See 2.1 for applicable regulations.

4.4.3 Proposed Simulations for Flight Testing

- Aircraft performance, flight characteristics, and systems simulations, including but not limited to flight dynamics, flight controls, ground reactions, and propulsion; should be specific (see Table B1)
- Other required simulations and emulations should be generic, representative, or specific (see Table B2) depending on the level of fidelity required for the test cases.
- Conformity options include:
 - Simulated aircraft hardware
 - Emulated aircraft software, if based on data generated by the conformed configuration software or functionally equivalent
 - Emulated interfacing systems hardware and software
 - Conformed hardware
- If required, a flight deck/ground station should be suitable for evaluation.

4.4.4 Scalable Simulations for Flight Testing

- The scale and fidelity of the simulations/models should be appropriate for the test being performed.

4.4.5 Design and Reference Data for Flight Testing

- Document the design and reference data source(s).

4.4.6 Limitations of the Simulation for Flight Testing

- Limitations should be provided for parameters that affect the operation and/or behavior of the aircraft.

4.4.7 Testing Methods for Flight Testing

- Human-in-the-loop
- Human-on-the-loop
- Human-over-the-loop
- Bench/rig testing

4.4.8 Witnessing for Flight Testing

- The Simulation Plan should propose what tests will require witnessing and determine the Certification Authority or delegated representative.
- For tests that do not require witnessing, the Simulation Plan should propose how the executed tests and results will be submitted to support the Simulation Test Plan.

5. SIMULATION VALIDATION PLAN AND SIMULATION VALIDATION REPORT

5.1 Overview

The Simulation Validation Plan and Simulation Validation Report ensure that the results are accurate, complete, and reproducible. The objective is to prove that simulation can be used in lieu of traditional methods of compliance. This process involves comparing the simulation outputs to experimental or observed data from the actual system to ensure that the model behaves as expected under various conditions.

- Simulation validation should include a plan and a report.
- The Simulation Validation Plan should include the following:
 - Description of models that are used
 - Establishment for each individual model or simulation that it accurately and correctly reflects the specific characteristics/trends
 - Definition of validation requirements, including tests, reference data collection criteria, and tolerances
- The Simulation Validation Report should include the following:
 - Summary statement of the simulation validation
 - Validation results
- Validation data should be retained and be available to the Certifying Authority upon request.
- When the Simulation Validation Report is accepted, it is then ready for use to support the Simulation Test Plan.

5.2 Simulation Validation Plan

This Plan defines a set of tests, criteria, and tolerances that the simulation should meet to be considered an accurate representation of the system under test.

This Plan should verify that the simulation is being exercised properly given a predetermined set of inputs and expected outputs, based on previous hardware and software testing or other testing as appropriate (e.g., bench testing, flight testing, wind tunnel testing, etc.).

5.2.1 Simulation Validation Objective 1: Model Description

Describe the mathematical, physics, and logical models that will be used for simulation.

This Plan should describe the models that will be used for simulation and their source. This includes, but is not limited to, static, dynamics, system, and environmental models. Some examples of model types include the following:

- Graphic representations. Used to validate spatial representations either with respect to the end users' environment or the user interface with the operator.
- Systems model. Used to validate normal and non-normal performance of a particular component or system in a stand-alone environment, often with representative inputs. This might be physics-based, empirical, or a hybrid combination of the two.
- Performance simulation. Focused on the static and dynamic characteristics to see how the simulation of the aircraft will behave across its expected range of inputs.

The simulation environments can include the following:

- Software simulation
- Rehosted hardware: original software that is run on the real processor but not in the actual hardware
- Retargeted hardware: original software that has been recompiled to run on a different processor
- Replicated hardware: a reproduction of the actual hardware and software
- Hardware emulation
- Actual hardware

Model sources:

- Internally developed
- Externally procured
- Industry standard models

5.2.2 Simulation Validation Objective 2: Validation Test

Document the validation tests that will be executed to prove equivalence between simulation and actual system operation.

A validation test consists of a set of procedures performed to exercise the model in order to determine the level of accuracy of its response against reference data.

Tests should be applied against an individual model or with increasing levels of complexity up to a fully integrated simulation/system.

These consist of static and dynamic cases across a number of different initial conditions.

Tests should cover the range and granularity of the envelope and environment being considered for certification .

5.2.3 Simulation Validation Objective 3: Validation Criteria and Tolerances

Propose model validation criteria and tolerances.

The applicant should propose the criteria and tolerances to the Certification Authority.

Criteria and tolerances can vary depending on the model or simulation that is being compared against reference data or the specific operational scenario that is being simulated.

Validation criteria should be defined based on the intended use of the simulation for certification.

Parameters could be time and/or frequency based.

Parameters should follow the characteristics and trends of the reference data.

Flight testing criteria and tolerance examples are provided in Appendix A. This is not a fully inclusive list, and the tolerances are the starting point for discussion with the Certification Authority.

Validation criteria for systems testing includes, but is not limited to, the following:

- Signal inputs and outputs
- Power states
- Degraded states
- Failure effects
- Static and dynamic responses
- Response time

Validation criteria for human factors testing includes, but is not limited to, the following:

- All validation criteria from 5.2.3
- Interactions (ergonomics, biomechanical force, errors)
- Spatial representation (out-the-window view, head worn display, synthetic vision)
- Cues (tactile, visual, aural, motion)
- Procedures, checklists, and operating manuals required for operation

Validation criteria for flight testing includes, but is not limited to, the following:

- Tolerance bands (e.g., upper/lower limits)
- Margins (e.g., phase margins)
- Operational limits and boundaries

5.2.4 Simulation Validation Objective 4: Reference Data Collection Criteria

Document reference data that will be used to validate the simulation.

Reference data used to validate the simulation should be collected from a conformed platform or component. The data collection may consider the following criteria, as applicable:

- Range
- Resolution
- Accuracy
- Sampling rate
- Calibration
- Sensor location

The reference data should align with what was documented in the Simulation Plan (Simulation Plan Objective 6; see 4.1.6). Any differences between the plan and the reference data that were ultimately used for validation should be discussed in detail.

5.3 Simulation Validation Objective 5: Simulation Validation Report

Conduct validation testing and document the results.

The Simulation Validation Report should include the following information:

- Summary statement describing the accuracy of the simulation against the reference data.
- Table containing information on each test from the Simulation Validation Plan, including the test, initial conditions, pass/fail, configuration information, comments, reference data, and applicable regulations.
- Disposition of results that did not pass.
- Description of simulation limitations that may impact testing for certification.
- Document deviations to the Simulation Plan.
- Reference to supporting data.

6. SIMULATION TEST PLAN AND EXECUTION

6.1 Overview

The Simulation Validation Report should be accepted by the Certifying Authority prior to the review of the Simulation Test Plan.

The Simulation Test Plan(s) defines the test procedure for the simulation, defines how data will be generated to show compliance to the applicable regulations, and defines who should conduct and witness this activity.

- The Simulation Test Plan(s) defines tests in a manner similar to traditional test plans, but in this case compliance is shown by simulation.
- This document requires approval by the Certification Authority or the delegated representative.
- The Simulation Test Plan(s) defines simulation configuration, environmental conditions, conformity (hardware, displays, pilot touch points), and software and hardware configuration control.
- The Simulation Test Plan(s) defines the prerequisites to execute the tests.

6.2 Simulation Test Plan

The Simulation Test Plan should include the following information:

6.2.1 Introduction/Purpose

- Signature page or equivalent

6.2.2 System Description

- Description of what is to be tested
- List of all equipment necessary to conduct test

6.2.3 Simulation Test Plan Objective 1: Prerequisites

Define any prerequisites.

- Define the prerequisites required to execute the Simulation Test Plan. This can include any in-process simulation construction work at the time of plan authoring, any programmatic tasks that need to be executed, supplier commitments that need to be met, etc.

6.2.4 Simulation Test Plan Objective 2: Simulation Environment

Identify the appropriate environment.

- Identify the environment used for simulation testing. This can include such varied environments as FFS, FTD, or Desktop. If multiple simulations across different environments are used to show compliance with multiple regulations, all environments should be identified and described.

6.2.5 Simulation Test Plan Objective 3: Configuration

Document the simulation configuration.

- Identify simulation configuration, environmental conditions, conformity (hardware, displays, pilot touch points), and software and hardware configuration control.

6.2.6 Simulation Test Plan Objective 4: Test Personnel

Identify the appropriate test personnel.

- Identify the organization, roles, and responsibilities required to correctly execute and witness the test. These should align with what was documented in the Simulation Plan for test witnessing requirements (Simulation Plan Objective 9; see 4.1.9).

6.2.7 Simulation Test Plan Objective 5: Instrumentation

Describe the test instrumentation that will be used.

The description of each test instrumentation device or software item should include the following, at a minimum:

- Description
- Unit
- Range
- Sampling rate
- Source

6.2.8 Simulation Test Plan Objective 6: Test Description

Document the test cases that will be run in the simulation.

Test standards vary by organization but should generally include the following data categories:

- Test/initial conditions
- Operational scenarios
- Applicable regulations/airworthiness standards
- Procedure
- Pass/fail criteria

The test cases should be in accordance with the test methods documented in the Simulation Plan (Simulation Plan Objective 8; see 4.1.8). If there are major differences between the planned test methods and the test cases in the Simulation Test Plan, these should be described in detail or the organization should revise the Simulation Plan accordingly.

6.2.9 Simulation Test Plan Objective 7: Safety

Identify critical safety information for the simulation test procedures.

- Test hazard analysis or reference
- Knock it off criteria

6.2.10 Simulation Test Plan Objective 8: Data Analysis and Reporting

Document the information that will go into the Simulation Test Report.

The Simulation Test Plan should document which data will go into the Simulation Test Report, including for each data item:

- Traceability
- Exceptions
- Conclusion

6.2.11 References

Provide references to support the Simulation Test Plan.

6.3 Simulation Test Plan Objective 9: Test Execution

Conduct the simulation-based test procedures and generate test data for compliance.

The Simulation Test Plan should be approved by the Certification Authority prior to activity showing compliance.

Conduct the tests and gather the necessary data to demonstrate compliance using the simulation and procedures outlined in the Simulation Test Plan. The Certification Authority will observe this activity, either directly with specialists or, depending on the applicant, through delegated representatives.

7. SIMULATION TEST REPORTS

7.1 Overview

The Simulation Test Report is similar to a Flight Test Report but documents a different method of compliance than the traditional reports.

- Documents the execution of the simulation, the subsequent test results, the regulations for showing of compliance, and includes commentary of how compliance to the regulations has been shown.
- This report requires approval by the Certifying Authority or delegated representatives, with the approval indicating that compliance has been found.

7.2 Simulation Test Report Objective 1: Documentation

Document the results of the test activity in alignment with the Simulation Test Plan.

The Simulation Test Report documents the execution of the simulation test, the subsequent test results, and includes commentary of how compliance to the regulations has been shown.

The report should cover the following, in the context of the objectives that were presented, to be approved by the Certification Authority or delegated representative for the preceding documents:

- Applicable regulations
- Applicable test
- Traceability information
- Explanation of calculations necessary to evaluate data
- Analysis of the data
- Explanation of the results
- Deviations in configuration/version/test results
- Conclusion with compliance statement/signature page

7.3 Approval

This report requires approval by the Certifying Authority or delegated representatives, with the approval indicating that compliance has been found.

8. NOTES

8.1 Revision Indicator

A change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE G-35, MODELING, SIMULATION, TRAINING FOR EMERGING AV TECH

APPENDIX A - TOLERANCES

A.1 EXAMPLE TOLERANCES

There are no codified tolerances for modeling and simulation for certification. The closest equivalent are the tolerances used in the certification of flight simulation training devices (FSTDs). These are listed in the following references:

- FAA 14 CFR Part 60
- EASA CS-FSTD(A)
- EASA CS-FSTD(H)
- Transport Canada TP 9685E
- ICAO 9625 4th Edition
- RAeS Aeroplane Flight Simulation Training Device Evaluation Handbook, Volume 1,

Extracts of these are listed below. When submitting a Simulation Plan, these can be referenced and can be used for discussion with the Certification Authority when proposing tolerances to be met for certification.

Table A1

Parameter	Tolerance	Notes
Acceleration	±0.1 g	
Airspeed	±3 kts	CS-FSTD(A) (2) ±5 kts or ±5%
Altitude	±20 feet (6 m)	Takeoff condition
Altitude	±100 feet (30 m)	Approach condition, surface change dynamics
Angle - Attack	±1.5 degrees	
Angle - Attack	±2 degrees	Stall
Angle - Bank	±2 degrees	
Angle - Elevator	±1 degrees	
Angle - Heading	±3 degrees	
Angle - Nosewheel	±2.0 degrees	
Angle - Pitch	±1.5° or ±20%	
Angle - Pitch	±2 degrees	Stall
Angle - Rudder	±2.0 degrees	
Angle - Sideslip	±2.0 degrees	Part 60 (1) is ±2.5°
Angle - Spoiler	±3.0 degrees	
Angle - Stabilizer	±0.5 degree	
Angle - Throttle Lever	±5.0 degrees	
Distance	±5% or ±61 m (200 feet)	Ground acceleration time and distance
Distance	±7.5% or ±7.6 m (250 feet)	Rejected takeoff
Distance	±10%	One engine inop climb
Engine - EPR	±0.03%	CS-FSTD(A) (2) ±0.05%
Engine - N1	±3%	CS-FSTD(A) (2) ±5%
Engine - Torque	±3%	CS-FSTD(A) (2) ±5%
Force - Breakout	±2 pounds (0.9 daN)	Column and wheel; rudder is ±5 pounds (2.2 daN)
Force - Brake Pedal	±10% or ±5 pounds (2.2 daN)	
Force - Rudder Pedal	±10% or ±5 pounds (2.2 daN)	Takeoff condition

Parameter	Tolerance	Notes
Force - Stick/Column	$\pm 10\%$ or ± 5 pounds (2.2 daN)	Takeoff condition
Force - Stick Pusher	$\pm 10\%$ or ± 5 pounds (2.2 daN)	Takeoff condition
Force - Wheel	$\pm 10\%$ or ± 3 pounds (1.3 daN)	
Fuel Flow	$\pm 5\%$	
Load Factor	± 0.1 g	
Rate - Climb	$\pm 5\%$ or ± 100 FPM (0.5 m/s)	
Rate - Descent	$\pm 5\%$ or ± 200 FPM (1.0 m/s)	
Rate - Emergency Descent	$\pm 5\%$ or ± 300 FPM (1.5 m/s)	
Rate - Pitch	± 0.15 (deg/s) body pitch rate or $\pm 20\%$ of peak body pitch rate	Small controller inputs
Rate - Roll	± 0.2 (deg/s) or $\pm 10\%$ roll rate	Step input
Rate - Roll	± 0.15 (deg/s) body roll rate or $\pm 20\%$ of peak body roll rate	Small controller inputs
Rate - Yaw	± 0.15 (deg/s) body yaw rate or $\pm 20\%$ of peak body yaw rate	Small controller inputs
Rate - Yaw	± 2 (deg/s) yaw rate	Landing
Rate - Trim Rate	$\pm 10\%$ (deg/s)	
Time	$\pm 5\%$	Acceleration/deceleration
Time	$\pm 10\%$	One engine inop climb
Turn Radius	± 0.9 m (3 feet) or $\pm 20\%$ of aeroplane turn radius	Minimum radius turn
Turn Rate	$\pm 10\%$ or ± 2 deg/s turn rate	Rate of turn versus nosewheel steering angle

APPENDIX B - MODEL FIDELITY FOR TESTING

B.1 MODEL FIDELITY LEVELS

ICAO has defined four levels of model capabilities in its 9625 document as follows.

Table B1

Level	Aircraft Simulation	Cueing Simulation	Environment Simulation
None (N)	Not required.	Not required.	Not required.
Generic (G)	Not specific to aeroplane model, type, or variant.	Generic to an aeroplane of its class. Simple modeling of key basic cueing features. For visual cueing only: generic visual environment with perspective sufficient to support basic instrument flying and transition to visual from straight-in instrument approaches.	Simple modeling of key basic environment features.
Representative (R)	Representative of an aeroplane of its class (e.g., four-engine turbofan aeroplane). It does not have to be type specific.	For sound and motion cueing only: replicates the specific aeroplane to the maximum extent possible. However, physical limitations currently only provide representative, not specific, cues. For visual cueing only: representative of the real-world visual environment and perspective.	Representative of the real-world environment.
Specific (S)	Replicates the specific aeroplane.	Applicable to visual cueing only: replicates the real-world visual environment and (infinity) perspective.	Replicates the real-world environment, as far as required to meet the training objectives, for any specific location.

B.2 EXAMPLE FIDELITY LEVELS FOR TEST ACTIVITIES

Table B2 contains a set of example test activities for which simulation may be used for certification, but the applicant should negotiate the specific test activities and simulation fidelity levels with the Certification Authority.

Cueing simulations may be required depending on the involvement of a human-in-the-loop.

Test Activity	Aerodynamics Model	Mass Properties Model	Equations of Motion Model	Atmospheric and Wind Models	Air Data, Inertial Reference Models	Ground Reactions Model, incl NWS	Propulsion System Model	Flight Controls Law Models	Flight Actuator Models	Cockpit Control Inceptor Models	Energy and Energy Management Models	Aircraft Systems Models	Flight Deck Configuration	Human Factors Modeling	Environment Models	Integration Level
Air Data System and RVSM Certification	S	S	S	R	S	R	R	S	S	R	R	S	S	S	R	S
Artificial Ice Shapes Certification	S	S	S	S	R	N	S	S	S	S	S	S	S	N	S	S
AFCS Certification	S	S	S	S	S	S	S	S	S	S	S	S	S	N	R	S
Avionics Equipment Cooling Certification	N	N	N	R	N	N	R	R	R	R	R	S	S	S	R	S
Brakes, Antiskid, and TPMS Certification	S	S	S	S	S	S	S	R	R	S	S	S	S	S	S	S
Climb Performance Certification	S	S	S	S	S	N	S	S	S	R	S	R	R	N	S	S
CMF Datalink and Cockpit Printer Certification	R	N	N	R	S	N	N	N	N	N	N	R	S	S	R	S
Cold Weather Operation Certification	S	S	S	S	S	S	S	S	S	S	S	S	S	N	S	S
Communication and Navigation Radio Systems Certification	R	R	R	R	S	R	N	N	N	N	N	S	S	S	N	S
Crew Workload and Human Factors	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Data Concentration and Network Certification	R	R	R	R	S	R	S	N	N	N	N	R	R	S	R	S
Electrical Power System Certification	S	S	S	R	R	R	S	N	N	N	N	S	S	S	R	S
Electronic Display System including Touch Screen Controllers (TSC)	R	R	R	R	S	S	S	R	R	R	R	S	S	S	R	S

Test Activity	Aerodynamics Model	Mass Properties Model	Equations of Motion Model	Atmospheric and Wind Models	Air Data, Inertial Reference Models	Ground Reactions Model, incl NWS	Propulsion System Model	Flight Controls Law Models	Flight Actuator Models	Cockpit Control Inceptor Models	Energy and Energy Management Models	Aircraft Systems Models	Flight Deck Configuration	Human Factors Modeling	Environment Models	Integration Level
Engine Starts, Operability, Go-Around Thrust, and TR Operation Certification	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
EGPWF Certification	R	R	R	R	R	R	S	R	R	R	S	S	S	S	S	S
Field Performance Certification	S	S	S	S	S	S	S	S	S	S	S	S	S	N	S	S
Takeoff Field Performance Certification	S	S	S	S	S	S	S	S	S	S	S	R	S	N	S	S
Landing, RTO, and TR Effectiveness Certification	S	S	S	S	S	S	S	S	S	S	S	R	S	S	S	S
FCS with Active Control Sidestick Certification	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
FIKI Certification	S	S	S	S	S	N	S	S	S	S	S	S	S	N	S	S
FMS Certification	S	S	S	S	S	S	S	S	S	R	S	S	R	S	R	S
Fuel System Certification	N	N	N	R	R	R	S	R	R	R	S	S	R	N	S	S
HUD and EVS Certification	R	R	R	N	S	N	N	R	R	R	R	S	S	S	R	S
Maximum Landing Field Elevation Operation Certification	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Power Plant Ventilation, Cooling, and Hot Weather Operation Certification	S	S	S	S	S	R	S	R	R	R	S	S	S	S	S	S
Hydraulic System Certification	R	R	R	R	R	S	S	S	S	S	R	S	R	R	R	S
Landing Gear System Certification	S	S	S	S	S	S	S	R	R	S	R	S	S	N	R	S

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